JOURNAL OF THE AMERICAN ROCKET SOCIETY

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NUMBER 79 DECEMBER, 1949

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JOURNAL OF THE AMERICAN ROCKET SOCIETY

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ROBERTSON YOUNGQUIST, Editor

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Published Quarterly by The American Rocket Society, Inc.

Journal of The American Rocket Society, December, 1949, Volume Number 79. Published quarterly by The American Rocket Society at 20th and Northampton Streets, Easton, Pa., U. S. A. The Editorial Office is located at the Engineering Societies Building, 29 West 39th Street, New York 18, N. Y. Price, $1.00 per copy, $4.00 per year. Entered as second-class matter at the Post Office at Easton, Pa., under the Act of March 3, 1879.

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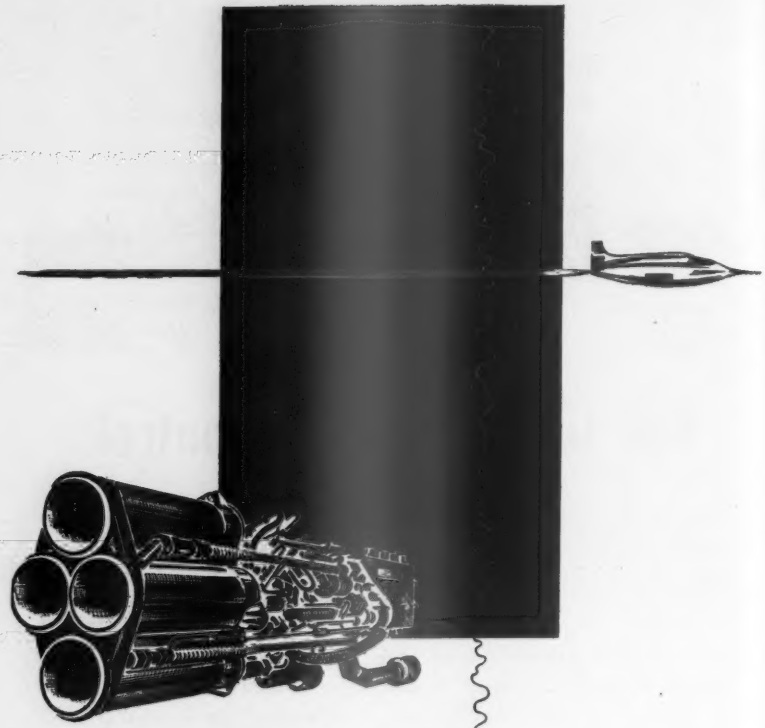

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Number 79 ROBERTSON YOUNGQUIST, *Editor* December, 1949

A THEORETICAL AND EXPERIMENTAL INVESTIGATION OF ROCKET-MOTOR SWEAT COOLING

By Joseph Friedman

Supervisor, Propulsion Research, North American Aviation, Inc., Los Angeles, Calif.

A theoretical and experimental analysis of the gas-phase transpiration-cooling process is presented for the case where the coolant fluid has physical properties identical to those of the mainstream fluid. An equation is derived, relating the temperature of the porous wall to the rate of coolant flow. Good agreement is found between the theoretical analysis and the experimental results using air as the sweat coolant.

Nomenclature

c_p = specific heat of coolant, Btu/lb F
G = coolant flow, lb/hr/ft²
h = coefficient of heat transfer, Btu/-hr/ft²/F
h' = apparent coefficient of heat transfer, for the sweat-cooling process, Btu/hr/ft²/F
k = thermal conductivity of fluid in boundary layer, Btu/hr/ft² (F/ft)
Nu = Nusselts number
q = rate of heat transfer per unit area, Btu/hr/ft²
q_w = rate of heat transfer per unit area into porous wall, Btu/hr/ft²
r = ratio of temperature drop across laminar sublayer to over-all temperature drop, i.e., $r = (t_\delta - t_w)/(t_g - t_w)$
Re = Reynolds number
t = temperature, F
t_g = mean mainstream gas temperature, F
t_{max} = maximum gas temperature, F
t_o = initial temperature of coolant entering coolant manifold, F
t_w = hot side porous wall temperature, F
t_δ = temperature at interface between boundary layer and turbulent core, F
u = fluid velocity, fps
u_{max} = maximum mainstream fluid velocity, fps
$\bar{u}$ = average fluid velocity, fps
u_δ = velocity at interface between boundary layer and turbulent core, fps
x = radial distance from inner wall surface, ft
δ = thickness of laminar sublayer, ft
ϕ = dimensionless group equal to Gc_p/h

Introduction

THE conventional method of rocket-motor cooling consists of using one of the propellant components as a regenerative coolant, by ducting it through a cooling jacket on the outside of the motor wall. This method limits the choice of propellant combinations to those having a component suitable for use as a coolant. The general specifications for such a coolant are: (1) Liquid at ambient temperatures; (2) high boiling point; (3) stability at high temperatures and pressures; and (4) high specific heat.

The above specifications place a severe limitation upon the choice of propellant combinations. Many high-energy propellant combinations, such as the hydrogen-oxygen and hydrogen-fluorine systems, cannot be used in conventionally cooled rocket motors because neither of the components is suitable as a regenerative coolant.

Considerable interest has been shown in an alternative method of rocket cooling known as transpiration (or sweat) cooling, because it eliminates the above restrictions. This method uses a porous motor wall through which a coolant, either gaseous or liquid, is transpired in a direction opposite to that of the heat flow.

It is the purpose of this paper to present the experimental work in transpiration cooling performed at North American Aviation, and to develop a simplified theory of gas-phase transpiration cooling which will adequately correlate the experimental data, and provide engineers with a basis for designing in sweat-cooling applications.

Experimental Apparatus

The apparatus used in these tests is shown schematically in Fig. 1. A 6-inch-diameter turbojet-can-type kerosene burner connected to the plant air supply was used as a source of heated air. The air was then passed through a flow straightening section of 10 diameters in length at which point a thermocouple probe was used to make a radial survey of the temperature profile. The 6-inch section was then connected by a reducing cone to a thermally insulated, 3-inch calming section which in turn connects immediately to the test specimen. The test specimen was a 6-inch-long, 3-inch-inside-diameter, $^3/_{16}$-inch-thick manifolded porous nickel cylinder. The inside wall temperature of the porous test specimen was measured by means of a suitably installed thermocouple.

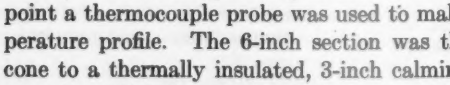

FIG. 1 SCHEMATIC DIAGRAM OF SWEAT-COOLING TEST APPARATUS

Air was used as a coolant in the data presented here. All wall temperatures reported in this paper were measured at a length-to-diameter ratio of 1.85.

Experimental Data

The data given in this report cover the following ranges:

Hot gas temperature	800 to 1300 F
Reynolds number	2.5×10^4 to 2.5×10^5
Coolant flow rate	50 to 400 lb/hr/ft^2
Length-to-diameter ratio	1.85

The local values of h, the heat-transfer coefficient for conventional heat transfer in pipes, were deduced for each run from the experimental data by extrapolating to zero coolant flow, plots of h', observed coefficient, versus coolant flow rate. Fig. 2 shows a typical extrapolation. Then, h' was calculated as the coefficient needed to multiply the temperature potential $(t_g - t_w)$ to account for the heat absorbed by the coolant. Thus the defining relationship for h' is:

$$h' = Gc_p(t_w - t_o)/(t_g - t_w) \quad [1]$$

Fig. 3 shows a plot of Nusselts versus Reynolds number based upon the values of h' obtained by the previously described extrapolations. It is seen that the equation:

$$Nu = 0.023\ Re^{0.8} \quad [2]$$

represented by the dotted line in the figure, adequately correlates the data. In comparison, the equation recommended by McAdams[1] for heat transfer for gases in long tubes is:

$$Nu = 0.02\ Re^{0.8} \quad [3]$$

It is apparent that the measured rates of heat transfer are about 15 per cent higher than accepted values for long tubes. This is probably due to the short length-to-diameter ratio of the test specimen, and the roughness of the porous surface.

The observed variation of sweat-cooled wall temperature with coolant

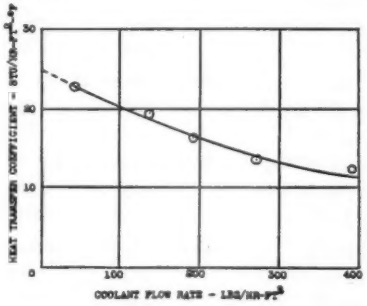

FIG. 2 APPARENT HEAT-TRANSFER COEFFICIENT VERSUS COOLANT FLOW RATE FOR RUN 9

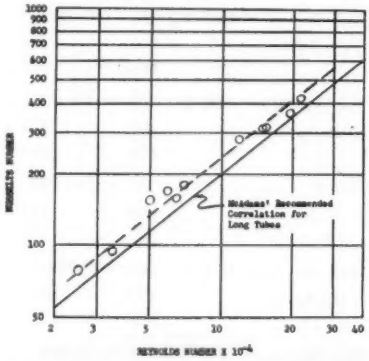

FIG. 3 NUSSELTS NUMBER VERSUS REYNOLDS NUMBER

[1] "Heat Transmission," by W. H. McAdams, 2nd ed., 1942, McGraw-Hill Publishing Company, Inc., New York, N. Y.

flow rate is shown in Fig. 4 for several typical runs. The data upon which this report was based, is summarized in Table 1.

Theory

It is of engineering interest to be able to predict the variation of wall temperature with coolant flow rate. It is the purpose of the following analysis to obtain a simple theoretical relationship between wall tem-

TABLE 1 EXPERIMENTAL RESULTS OF SWEAT-COOLING MEASUREMENTS

$L/D = 1.85$ ($t_o = 70$ F)

Run 1: $t_g = 1200$ F	$Re = 120{,}000$ (Fig. 4)				
G (lb/hr/ft²)	402	268	143.5	86.3	43.1
t_w(F)	280	385	625	795	960
Run 2: $t_g = 1000$ F	$Re = 50{,}000$ (Fig. 4)				
G (lb/hr/ft²)	393	234	173	115	44.9
w (F)	130	219	310	408	654
Run 3: $t_g = 1230$ F	$Re = 25{,}000$				
G (lb/hr/ft²)	393	225	144	118	42.8
t_w (F)	112	178	245	348	622
Run 4: $t_g = 1170$ F	$Re = 60{,}000$				
G (lb/hr/ft²)	393	273	191.5	139	43.9
t_w (F)	198	260	356	473	815
Run 5: $t_g = 830$ F	$Re = 215{,}000$				
G (lb/hr/ft²)	402	230	186	126	...
t_w (F)	253	369	443	510	...
Run 6: $t_g = 920$ F	$Re = 155{,}000$				
G (lb/hr/ft²)	383	278	182	129	...
t_w (F)	262	311	423	513	...
Run 7: $t_g = 1090$ F	$Re = 70{,}000$				
G (lb/hr/ft²)	392	254	201	144	108
t_w (F)	168	259	323	415	522
Run 8: $t_g = 1035$ F	$Re = 150{,}000$				
G (lb/hr/ft²)	402	278	220	148	95.8
t_w (F)	258	335	428	555	650
Run 9: $t_g = 950$ F	$Re = 195{,}000$				
G (lb/hr/ft²)	402	272	177	129	90
t_w (F)	275	368	487	566	650
Run 10: $t_g = 1333$ F	$Re = 35{,}000$				
G (lb/hr/ft²)	412	340	240	139	93.8
t_w (F)	108	135	203	331	461
Run 11: $t_g = 1317$ F	$Re = 65{,}000$				
G (lb/hr/ft²)	412	316	240	182	...
t_w (F)	212	270	344	450	...

perature, coolant flow rate, and the local heat-transfer coefficient as obtainable from conventional measurements or formulas.

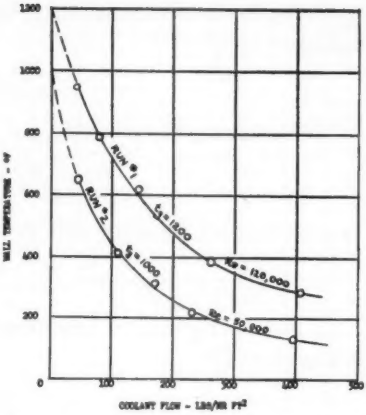

FIG. 4 POROUS WALL TEMPERATURE VERSUS COOLANT FLOW (SEE TABLE 1 FOR DATA ON ALL TEST RUNS)

In the case of turbulent flow, such as exists at high Reynolds numbers in circular pipes, the resistance to heat transfer between the fluid and the wall may be considered as the sum of two separate resistances: that of a laminar sublayer immediately adjacent to the wall; and that of the turbulent core. Actually, the boundary between the two zones is not clearly defined but is rather a transition zone sometimes referred to as the buffer layer. The simpler concept of two distinct zones will be used, however, as it is more amenable to the mathematical analysis proposed in this paper.

Any influence the coolant will exert upon the heat-transfer process will be mainly manifested in the laminar sublayer where conduction is the principal mode of heat transfer. There, the flow of coolant, countercurrent to the heat flow, will tend to carry back with it some of the heat, thus decreasing the effective coefficient of heat transfer. In the turbulent core, however, where the principal mechanism of heat transfer is convection, the low-velocity coolant can have but little influence.

Fig. 5 shows the type of temperature gradient that will exist when a porous wall is cooled by transpiration cooling.

For the case where the physical properties of the coolant are identical to those of the mainstream fluid, it can be shown by a simplified one-dimensional analysis that the differential equation describing the sweat-cooling heat-transfer process in the laminar zone is:

$$k\frac{d^2t}{dx^2} - Gc_p\frac{dt}{dx} = 0 \ldots\ldots [4]$$

A derivation of Equation [4] is given in Appendix I.

Evaluating Equation [4] for the following boundary conditions:

$$x = 0,\ t = t_w$$
$$x = \delta,\ t = t_\delta$$

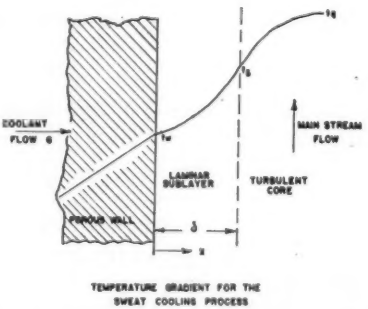

FIG. 5 TEMPERATURE GRADIENT FOR THE SWEAT-COOLING PROCESS

it is possible to obtain as the temperature-distance relationship in the boundary layer:

$$t = t_w + \frac{t_\delta - t_w}{e^{Gc_p\delta/k} - 1} (e^{Gc_px/k} - 1) \quad [5]$$

Differentiating Equation [5],

$$\frac{dt}{dx} = \frac{t_\delta - t_w}{e^{Gc_p\delta/k} - 1} \frac{Gc_p}{k} e^{Gc_px/k} \quad [6]$$

as $q = k(dt/dx)$, Equation [6] can be written as:

$$q = \frac{t_\delta - t_w}{e^{Gc_p\delta/k} - 1} Gc_p e^{Gc_px/k} \quad [7]$$

To find q_w, the rate of heat transfer to the wall surface, let x equal 0 in Equation [7],

$$q_w = \frac{Gc_p (t_\delta - t_w)}{e^{Gc_p\delta/k} - 1} \quad [8]$$

but q_w must also be equal to the heat absorbed by the coolant in going from t_o, its initial temperature, to t_w, its exit temperature from the wall. Consequently,

$$q_w = \frac{Gc_p(t_\delta - t_w)}{e^{Gc_p\delta/k} - 1} = Gc_p (t_w - t_o) \quad [9]$$

or,

$$\frac{t_\delta - t_w}{t_w - t_o} = e^{Gc_p\delta/k} - 1 \quad [10]$$

Equation [10] gives the desired relationship between coolant flow and wall temperature. To make use of this equation, however, it is necessary to evaluate δ and t_δ. Let us consider for a moment a conventional heat-transfer process such as hot gases flowing through a water jacketed pipe. The rate of heat transfer will be:

$$q = h(t_g - t_w) \quad [11]$$

The rate of heat transfer can also be determined by writing an equation for heat conduction across the laminar sublayer,

$$q = \frac{k}{\delta} (t_\delta - t_w) \quad [12]$$

As the over-all rate of heat transfer given by Equation [11] is equal to the translaminar rate given by Equation [12],

$$h(t_g - t_w) = \frac{k}{\delta} (t_\delta - t_w) \quad [13]$$

If we let r represent the ratio of temperature drop across the laminar sublayer to the over-all temperature, i.e., $r = (t_\delta - t_w)/(t_g - t_w)$, Equation [13] may be written as:

$$\delta = kr/h \quad [14]$$

also, from the definition of r,

$$t_s = t_w - r(t_g - t_w) \quad [15]$$

We can now substitute [14] and [15] into Equation [10] to obtain:

$$\frac{t_w - t_o}{t_g - t_o} = \frac{r}{e^{\phi} - 1 + r} \quad [16]$$

where ϕ is a dimensionless group equal to Gc_p/h.

In order to estimate the value of r, it is possible to make use of the similarity between temperature and velocity profiles for gases flowing in tubes. Pannell,[2] in a series of velocity and temperature explorations across a turbulent air stream flowing in a heated vertical pipe, showed that the temperature ratio, $(t - t_w)/(t_{max} - t_w)$, at any point was equal within a few per cent to the velocity ratio, u/u_{max}, at that point. Utilizing this information, it is permissible to assume that r will be approximately equal to $u_s/\bar{u}$, where $\bar{u}$ is the mean velocity of the fluid. Prandtl[3] gives $u_s/\bar{u}$ as equal to $2.26/Re^{1/8}$, which for the Reynolds number range of these data, is about 0.5.

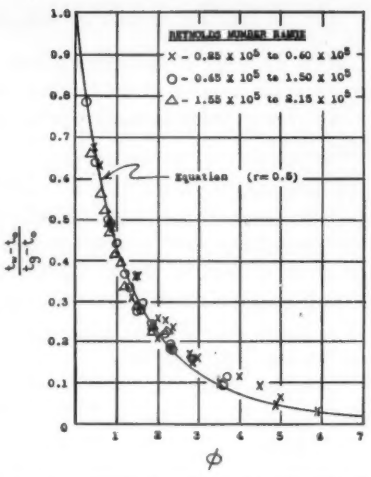

FIG. 6 TEMPERATURE RATIO VERSUS ϕ FACTOR

Fig. 6 compares the experimental data to a plot of Equation [16] assuming a value of r equal to 0.5. It is seen that the test data are correlated fairly well by the theoretical curve.

As the validity of the foregoing analysis depends upon the accuracy of the several idealizations employed, the fact that the experimental data do correlate to a reasonable degree of accuracy with the predicted relationships, serves partially to justify the idealizations made. It is indicated by both the foregoing analysis, and the experimental data, that a dimensionless parameter such as ϕ can be used successfully to correlate experimental data and to predict design information.

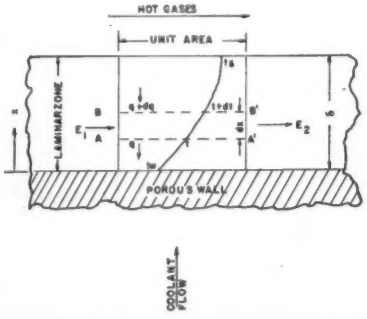

FIG. 7 TEMPERATURE GRADIENT IN A SWEAT-COOLED LAMINAR ZONE

[2] Report, Memorandum 243, J. R. Pannell, British Aeronautical Research Commission, June, 1916, H. M. Stationery Office, London.

[3] "Applied Hydro-and-Aeromechanics," by L. Prandtl and O. G. Tietjens, 1st ed., 1934, McGraw-Hill Publishing Company, Inc., New York, N. Y.

Appendix I

Heat Transfer Process in a Sweat-Cooled Laminar Zone. Fig. 7 represents a cross section of the laminar zone.

An energy balance may be written for the differential section shown in Fig. 7.

Energy in:

Through plane AB = E_1 (carried in with axial component of coolant flow)
Through plane BB' = $q + dq$
Through plane AA' = $Gc_p t$ (carried in with normal component of coolant flow)

Energy out:

Through plane $A'B'$ = E_2 (carried out with axial component of coolant flow)
Through plane AA' = q
Through plane BB' = $Gc_p(t + dt)$ (carried out with normal component of coolant flow)

Equating the energy in to the energy out:

$$E_1 + q + dq + Gc_p t = E_2 + q + Gc_p t + Gc_p\, dt \quad [17]$$

or,

$$E_1 + dq = E_2 + Gc_p\, dt \quad [18]$$

If fully developed equilibrium flow is assumed, the temperature and velocity gradients do not vary with axial length, and E_1 must equal E_2. Equation [18] then becomes:

$$dq = Gc_p\, dt \quad [19]$$

Writing Fourier's law for steady-state heat conduction:

$$q = k\frac{dt}{dx} \quad [20]$$

Differentiating Equation [20]:

$$\frac{dq}{dx} = k\frac{d^2t}{dx^2} \quad [21]$$

Combining Equations [19] and [21]:

$$k\frac{d^2t}{dx^2} - Gc_p\frac{dt}{dx} = 0 \quad [22]$$

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SUPERSONIC GUIDED MISSILES (PART II)

By R. E. Gibson

General Principle of Jet Engines

IN common with other primary sources of power all jet engines derive their energy from rapid and highly exothermic chemical processes producing hot gases at elevated pressures. Their mechanism for converting the elastic energy of these gases into the directed energy of motion of a vehicle is, however, much simpler than that of other power plants, being, in the last analysis, a most elementary application of Newton's Third Law of Motion, "To every action there is an equal and opposite reaction." Essentially, a jet engine consists of a tube closed or constricted at the front end and provided with a nozzle of some sort at the rear end. In this tube by a suitable chemical process gas is raised to a high level of elastic energy (the molecules attain high velocities or momenta) and allowed to flow out through the nozzle. The tube and its components exert a force on the hot, compressed gases causing them to be expelled through the nozzle. This we may call the "action." In turn the gases exert an equal force in the opposite direction on the motor and its components. This we may call the "reaction" which propels the vehicle in the forward direction.

The simple picture just presented brings out two points of fundamental importance in the consideration of jet engines. (1) The jet itself is not analogous to a propeller, but is rather a substitute for the air against which the propeller drives. The gases of the jet by their inertia provide a platform in space against which the engine can push in order to gain forward momentum. Thus, jet engines such as rockets that do not depend on atmospheric oxygen as a reactant in the energy-producing process will develop thrust in free space. (2) The important physical quantity to be considered in connection with the action of jet engines is momentum (mv) rather than energy ($^1/_2mv^2$). The momentum in the forward direction of the engine and its vehicle is equal to the momentum in the rearward direction of the jet gases, which is the product of their mass times their effective velocity. Since the effective velocity rises as the square root of the absolute temperature, it will be seen that the propulsive action of a jet is proportional to the mass-flow and the square root of the gas temperature.

It will be recalled that the energy of a gas varies directly with its temperature, while the momentum varies as the square root of the temperature. If the total mass-flow is very small, enormous gas temperatures or large supplies of energy will avail little in providing the vehicle with momentum. This is of interest in considering new sources of propulsion

Presented at a joint meeting of the Institute of Aeronautical Sciences and the American Rocket Society, New York, N. Y., Feb. 8, 1949.

[1] Continued from September, 1949, issue of ARS JOURNAL. See pages 129–140.

energy, for example, nuclear fission, as well as in considering limits set by materials or by regular fuels.

Although the general principles of jet action are extremely simple, the calculation of the net thrust of a given type of engine is somewhat more complex in that we must sum up all momentums and forces involved to determine the resultant. In such cases it is convenient to employ the well-known Momentum and Energy Theorems. For cases where velocity and flow are uniform over each cross section of a duct whose wall is a body of revolution, as in a rocket or ramjet, we may write

$$F_{21} = A_2(p_2 + \rho_2 v_2^2) - A_1(p_1 + \rho_1 v_1^2) \quad [2]$$

where F_{21} is the resultant of all normal and tangential forces exerted by the flowing gas on the walls of the duct between two cross sections labeled 1 and 2, and where A is the cross-section area, p the pressure (static), ρ the density of the gas, and v the velocity. This relationship is general enough to warrant defining $P \equiv A\ (p + \rho v_2)$ as the "stream thrust" and noting that the force,

$$F_{21} = P_2 - P_1 \quad [3]$$

An example of the use of this relationship is the calculation of the thrust of a rocket. Here $P_1 = 0$ since $A = 0$ at the front end of a rocket, if we neglect the inflow of fuel. Hence $F = P_2A_2 + A_2\rho_2 v_2^2$ but $A_2\rho_2 v_2$ is the mass rate of flow of gas through the nozzle exit ($\dot{m}$) and v_e is λv_e the effective gas velocity or exhaust velocity. Therefore

$$F = P_2A_2 + \dot{m}\,\lambda v_e$$

which is the well-known equation for the thrust of a rocket (λ being a divergence constant close to unity), if p measures in gage pressure. In absolute units the relation becomes

$$F = (p_2 - p_a)A_2 + \dot{m}\,\lambda v_e \quad [3a]$$

We shall refer again to this argument in a discussion of ramjets.

Auxiliary Propulsion of Guided Missiles

A lengthy analysis of the situation will show that in most cases it is important to bring a missile up to cruising speed as rapidly as is consistent with acceleration limitations arising from structural strength or delicacy of components. This means that a desirable auxiliary propulsion system is one capable of giving high thrust for a relatively short time. For these purposes the solid-fuel rocket is outstanding from the point of view of performance, simplicity, reliability, and expendability. When large missiles are considered, liquid-fueled rockets may become important sources of

auxiliary propulsion because of size limitations to solid-fuel rockets. The boundaries of the solid rocket's usefulness, however, seem to expand rather than contract as the subject is explored and these limitations are not yet in sight.

You will recall that the velocity increment V given to a rocket-powered assembly when a mass of propellant M_P is exhausted through the nozzle is given in terms of the effective gas velocity or specific impulse v_e, the payload M_m, and the deadload M_R by the relation

$$V = v_e \ln \left(1 + \frac{M_P}{M_m + M_R}\right) \quad [4]$$

The main development problem connected with auxiliary propulsion systems is to obtain the required velocity increment V with as small a mass of propellant M_P as possible. We have two variables to play with, v_e and M_R, or rather M_R/M_P, the ratio of dead load to propellant, the dead load consisting of the container, nozzle, stabilizing fins, and other appurtenances. An example will show that improvement of v_e or of M_P/M_R pays huge dividends. Suppose we wish to accelerate a missile of mass M_m to 2000 fps, that a propellant with specific impulse $v_e = 6000$ fps is available, and that by engineering design we can make $M_R/M_P = 1$. Applying Equation [4] in the modified form

$$M_P = \frac{M_m y}{\left(1 - \frac{M_R}{M_P} y\right)} \quad [5]$$

where

$$y = \text{Antilog}\left(0.4343 \frac{V}{v_e} - 1\right)$$

we see that $M_P = 0.66\, M_m$. Hence, the total rocket weight is $1.32\, M_m$ or if our missile weighs 1000 lb we need a booster weighing 1320 lb. If, however, $v_e = 8000$ fps then $M_P = 0.398\, M_m$; the total booster is therefore 0.8 the mass of the missile, which means that an 800-lb rocket would accelerate the 1000-lb missile to the same speed. (It is noted that the effects of drag and gravity are not taken into account here and have little effect in the comparison.)

During the last few years real advances have been made in this country in the development of rockets for auxiliary propulsion. This work has reached a state where solid-fuel rockets, giving for short times thrusts considerably in excess of that developed by the V-2, have performed consistently in a reliable and reproducible manner.

Looking ahead we may predict that increase in reliability and a continuous increase in the propellant-to-dead-weight ratio will be the lines of advance in the near future. Improvement of the specific impulse is a much harder job, as the following considerations will demonstrate.

The thermodynamics of ideal gas flow in rockets leads to the result that

the specific impulse of a fuel in a rocket may be expressed exactly as follows:

$$v_e = 32.1\, I$$

$$I = 9.302\, f\left(\gamma, \frac{A_e}{A_t}, \frac{P_c}{P_A}\right) \sqrt{\frac{T_c}{M}} \qquad [6]$$

In this equation the term $f(\gamma, A_e/A_t, P_c/P_A)$ depends only on γ, the ratio of the specific heats of the gases, on design, and on operation parameters, and does not vary widely over the extreme range of these parameters. Its total variation is 1.6 to 2.6 and under practical conditions the range is now 2.0 to 2.2. No radical improvement in specific impulse is to be expected from adjustment of this term. The term $\sqrt{T_c/M}$ involves two other significant properties of the propellant, the flame temperature T_c and the molecular weight M. The average flame temperature of available propellants is about 2500 K. To double the specific impulse by temperature rise would require the use of propellants with flame temperature of 10,000 K. This presents engineering difficulties of considerable magnitude.

The average molecular weight of propellant gases in the carbon-hydrogen-oxygen-nitrogen system is about 24. By use of elements and compounds giving average molecular weight of 6, a twofold increase in specific impulse is possible.

This presents chemical, chemical engineering, and production problems of great magnitude, but where high performance is required the cost of these efforts may be justified.

Main Propulsion Systems for Supersonic Missiles

The purpose of the main propulsion system of a guided missile is to provide enough thrust to accelerate slightly against gravity and to overcome the retarding forces of normal and induced drag, thereby maintaining the speed of the missile within desired limits. For this purpose solid-fuel rockets, liquid-fuel rockets, or ramjets may be used; the choice depending on a number of considerations such as the range of the missile, the type of guidance system to be used and trajectory to be flown, limitations imposed on the size, shape, and density of the missile, etc. Generally speaking, solid-fuel rockets on account of their simplicity are preferable for short-range missiles, if the center of gravity shifts due to burning of the propellant are tolerable. Liquid-fuel rockets have a field of applicability at intermediate ranges, while for the larger ranges ramjets are preferable unless it is desired to use the missile along a purely ballistic trajectory and dispense with midcourse and terminal guidance. I would recall our earlier remarks about the importance of momentum and point out that generally speaking, rockets must employ higher flame temperatures than air-breathing engines to give comparable performance, since all the mass of gas ejected must be carried by the rocket, but in the air-breathing engine the at-

mospheric gases contribute to the momentum of the jet. Hence, the engineering problems arising from heat transfer from the gases to the structures are more severe in long-burning rockets than in ramjets.

Since the development of liquid-fuel rockets for missile propulsion involves essentially an extension of work already familiar to you through accounts of such missiles as the V-2, the Navy Aerobee, the Army Wac Corporal, and the more recently announced Consolidated Vultee 774 or North American NATIV of the Air Forces, the remainder of this paper will be devoted to ramjets which, although old in principle, are extremely new and novel in practice.

The Principles and Development of Practical Ramjets

The idea of a ramjet or athodyd as a propulsive device was conceived at least thirty-six years ago. A French engineer, Rene Lorin, is credited with having first proposed and patented such an engine in 1913. Later similar devices were patented in Hungary by Fono (1928) and in France by Leduc (1933). During World War II the Germans investigated ramjets and designed some excellent diffusers. There is no record of their having developed supersonic ramjets, but there are accounts of flight tests of subsonic ramjets attached to airplanes. In 1944 the Bureau of Aeronautics became interested in the subject under the inspiration of the studies of Bollay and Redding, and experimental work on subsonic ramjet combustion was started at Massachusetts Institute of Technology and the Bureau of Standards. Shortly thereafter work on subsonic ramjets for the Air Forces was begun in California by Marquardt and his associates. A major effort to develop supersonic ramjets for guided missiles was instituted at the beginning of 1945 at the Applied Physics Laboratory of The Johns Hopkins University, under sponsorship of the Bureau of Ordnance, U. S. Navy. In June, 1945, the development of thrust in excess of drag by a flying ramjet was first demonstrated, and was followed by numerous flight experiments with 6-in. ramjets which confirmed expectations based on theory.

Operation of a supersonic ramjet can be described as follows. The vehicle is moving rapidly through the air, having been boosted to velocity by an auxiliary propulsion system. The dynamic pressure set up by the relative motion of the missile and the atmosphere causes air to enter through the intake into a diffuser where the velocity is reduced and the pressure and temperature are raised. Near the exit of the diffuser fuel is injected into the air stream; mixing takes place and the whole moves into the combustion chamber where ignition occurs; the fuel burns and the temperature of the gases rises sharply. The burning gas attempts to expand in all directions—the walls constraining it to move parallel to the longitudinal axis. Expansion toward the forward end occurs, this slows down the incoming stream and produces further rise of the pressure in the diffuser. This pres-

sure reacts on the sloping walls of the diffuser, giving a forward thrust to the vehicle. According to the forward speed of the ramjet and the design of the diffuser this pressure reaches a limiting value, and when this is reached we may presume that the pressure is high enough to hold back the hot gases and to force them to move in the only other direction possible, namely, toward the exhaust.

You will see, therefore, that the reaction of the hot accelerating gases on the walls of the diffusers, through the medium of the high-pressure air propels the vehicle.

Ramjet Diffusers

The following conditions prevail at diffuser end of a ramjet traveling at design speed. Just ahead of the intake stands a normal shock wave or discontinuity in the flow which characterizes all supersonic phenomena. Ahead of the shock wave the air is moving (with reference to the vehicle) at supersonic speed, Mach number $M > 1$. As the air traverses the shock its velocity drops and its pressure and temperature rise discontinuously. This is the first compression stage in a ramjet engine. Behind the shock, where its velocity is now less than sonic, the air enters a subsonic diffuser or region of expanding cross-section area, where its velocity (Mach number) decreases further and the pressure and temperature continue to increase.

If M_1 and M_2 are the Mach numbers at the entrance and exit of the diffuser, respectively, then the pressure recovery may be computed by the relation

$$\frac{p_2}{p_1} = \left(\frac{p_i}{p_1}\right) M_1 \;\Big|\; \left(\frac{p_i}{p_2}\right) M_2 \qquad [7]$$

where (p_i/p_1), etc., are given by

$$\Phi = \frac{T_i}{T_1} = \left(\frac{p_i}{p_1}\right)^{\frac{\gamma-1}{\gamma}} = \frac{(\gamma-1)}{2}\left[M_1^2 + \frac{2}{\gamma-1}\right] = \left[\frac{\gamma-1}{2} M_1^2 + 1\right] \qquad [8]$$

Thus, the pressure at the exit of the diffuser depends on the entrance and exit Mach numbers M_1 and M_2 and on the pressure at the diffuser entrance. The entrance and exit Mach numbers depend on the properties of the gas and on ratio of the exit and entrance areas according to the relation

$$\frac{A_2}{A_1} = \frac{M_1}{M_2}\left\{\frac{1 + (\gamma-1)/2\, M_2^2}{1 + (\gamma-1)/2\, M_1^2}\right\}^{1/2(\gamma-1)} \qquad [9]$$

Curves giving A_2/A_1 as a function of Mach number are well known for air and other gases.[2] Provided care is taken in subsonic diffuser design this part of the compression can be made nearly reversible. It was noted above that the passage through the shock constituted the first step in the compression. As the incident or flight Mach number rises, the Mach number

[2] "Principles of Jet Propulsion and Gas Turbines," by M. J. Zucrow, John Wiley and Sons, Inc., New York, N. Y., 1948, 98 pp.

behind the shock decreases, according to the well-known Prandtl relation; the pressure ratio across the shock increases but the compression becomes more irreversible, i.e., the stagnation, or total pressure obtainable on complete deceleration, drops. For the same ratio of intake and exit areas in the diffuser, therefore, the exit Mach number drops as the missile speed increases, and the pressure rises but not as rapidly as if there were no irreversible shock losses.

It may be noted in passing that for flight Mach numbers up to approximately 2, the irreversible losses across a normal shock are not too serious but they rise rapidly with Mach number. In order to minimize such losses, diffusers with diagonal shocks have been devised so that the component of velocity normal to these shocks is considerably less than the missile velocity; hence, the incident Mach number is reduced. By this device and the use of multiple shocks the irreversibility of this stage of the compression is kept within reasonable limits.

Combustion Processes

Let us now look for a short time at the combustion chamber in a ramjet. A few figures will orient your thinking about the scale of the processes going on. To produce the necessary thrust the heat release per unit volume is quite high, being of the order of 60 million Btu per cu ft per hr in a typical supersonic ramjet. You will recall that a heat release of 6 million Btu per cu ft per hr is quite high for any ordinary furnace. This means that the fuel and air supply in a ramjet must be large and that mixing and combustion must be thoroughly efficient. The gas velocities in the ramjet combustion chamber are high, being of the order of 200 fps at the entrance and 3000 fps at the exhaust. The time available for mixing and combustion is, therefore, quite short. Indeed, the time elapsed between the entrance of the air and fuel into the combustion chamber and the expulsion of their reaction products at the exit is of the order of 5 milliseconds. It is not surprising that the design of combustion chambers with ancillary problems of fuel metering and ignition, control of mixing, methods of starting and maintaining combustion, cooling, and materials have occupied a great deal of thought and effort.

An over-all analysis of the combustion process and its relation to the diffuser process may be obtained simply from a consideration of the "steam thrust" equation which I have already outlined. If the cross-section areas at the entrance and exit of the combustion chamber are equal and if subscripts 1 and 2 refer to entrance and exit conditions, respectively, we may write for stream thrusts

$$P_1 = P_2 + \text{Burner drag} \quad [10]$$

and note that our design problem is to make the burner drag as small as

possible, so that for convenience we shall call it zero. Then by definition

$$p_1 + \rho_1 v_1^2 = p_2 + \rho_2 v_2^2 \quad [11]$$

Furthermore, we shall assume that the exit Mach number is unity which is the case in all supersonic ramjets, the pressure recovery being able to support a combustion-chamber pressure whose ratio to the atmospheric pressure is sufficient to ensure choking. With $M_2 = 1$ and with the usual relations for an ideal gas, Equation [11] may be transformed to

$$\sqrt{\frac{kT_1}{\gamma}} \frac{(1 + M_1^2\gamma)}{M_1} = \sqrt{\frac{kT_2(1 + \gamma)^2}{\gamma}} \quad [12]$$

where k is the gas constant and T is the stream temperature. Now the term on the right-hand side of Equation [12] depends only on the stream temperature of the gas at the exit of the combustion chamber, which is determined completely by the entrance temperature and more importantly the energy release in the combustion process. It has been given a symbol of its own, S_a, which may be called the air specific impulse but which depends on the efficiency of the combustion process and the fuel-to-air ratio—reaching a maximum in the vicinity of the stoichiometric value of this ratio.

It can easily be shown that S_a may be measured in terms of the thrust of a cylindrical burner supplied with air through a flexible right-angle bend in such a way that the entrance stream thrust is zero. S_a is, therefore, an observable property of the combustion process depending only on the properties of the gases and their flame temperature.

Equation [12] brings out the important point that S_a determines the Mach number M_1 at the entrance to the combustion chamber, which, of course, must be equal to the Mach number at the exit of the diffuser, if a proper match of both components is to be obtained. Since M_1 is of the order of 0.2, $(1 + M_1\gamma^2)$ differs little from unity; hence Equation [12] also shows that as S_a rises, M_1 falls.

We are now in a position to examine in detail some important features of ramjet performance. Let us picture a ramjet moving at flight Mach number M and so adjusted that the combustion process supports an M_1 such that the normal shock is on the rim of the vehicle; the missile is cruising at design Mach number. Now let the flight Mach number increase. This immediately reduces M_e, the Mach number of the air behind the shock, which causes a drop in M_1, the Mach number at the diffuser exit, since the ratio of intake to exit areas is unchanged. However, the combustion process requires that M_1 remain constant; the shock, therefore, moves into the diffuser until a large enough entrance area is reached to raise M_1 to its original value.

A state of affairs called "swallowed shock" is set up, and even though we are expending the same amount of fuel per unit time (S_a constant), we lose thrust because of the low pressure area in the diffuser ahead of the shock.

The shock can be forced out to the rim by increase in the fuel-to-air ratio, but the recovery in thrust is paid for by increased fuel consumption. If the exit of the combustion chamber could be constricted the efficiency would be recovered, since the lower M_1 could be supported with the same fuel-to-air ratio, i.e., the S_a.

If the flight Mach number decreases then M_e and hence M_1 increase. To restore M_1 to the value demanded by the combustion process the shock moves forward from the rim, and air that would enter the diffuser under design conditions is now spilled over, or the effective entrance area decreases so that the ratio of M_1/M_e diminishes until M_1 returns to the value dictated by the combustion requirements. This regime of "detached shock" with attendant spill-over again reduces the efficiency. Reduction in S_a by reduction of fuel-to-air ratio will restore the shock to the rim, but serious drop in thrust will result. A mechanism for opening up the exit of the combustion chamber would, however, restore the design balances, increasing the thrust for the same fuel consumption. It will be seen, therefore, that a ramjet with fixed diffuser and exit nozzle can be designed to give fully efficient operation at only one flight Mach number, and that at higher or lower Mach numbers loss of thrust or increased fuel consumption occurs even with fuel meters for adjusting the fuel-to-air ratios. Within limits compromises that are not too costly may be effected, but the ideal flexibility can be achieved only with variable area ratio diffusers or variable combustion-chamber exit nozzles.

Attainment of optimum over-all efficiency of a ramjet as measured by the thrust coefficient depends on matching the diffuser and the combustion chamber and ensuring that both are operating with irreversible losses that are as low as possible, i.e., the drag losses in diffuser and combustion chamber must be kept to a minimum.

The foregoing brief account of the operation of a ramjet has covered the general principles and certain applications which are peculiar to this type of engine. There are many other aspects that are of interest and significance, but a discussion of them must be deferred to another occasion. You will have noticed that the ramjet is not quite as simple as the popular name, "flying stovepipe," would imply. To be sure it has no moving parts or other complicated mechanical components, but its design requires a detailed knowledge of complex gas-flow regimes, mixing phenomena, and ignition and combustion processes under extremely high rates of flow. The development of such an engine requires a large amount of empirical and experimental work which is quite impossible unless methods for simulating flight phenomena in the laboratory are worked out. Much of the effort of the Bumblebee project has been devoted to isolating the variables which are of significance in flight and devising laboratory methods for reproducing them quantitatively. It is felt that an important contribution to ramjets in the present state of the art is to establish exact correlations between

laboratory experiments and behavior in free flight, and to isolate and develop an understanding of these factors which are critical in scaling ramjets from one size to another. With this in view all flight vehicles are equipped with telemetering equipment to record the change of significant variables during flight experiments in order to establish a quantitative correspondence with laboratory tests.

Conclusion

The peacetime application of rockets and ramjets is a question in which we are all interested. It seems that cheap and thoroughly reliable solid-fuel rockets will find numerous peacetime applications wherever relatively high thrusts are required for moderately short times, say up to one minute. Assisting the take-off of airplanes is one example, but many others may occur to you. Liquid-fuel rockets have already proved their value as methods of taking research laboratories into the reaches of the upper atmosphere and thereby giving us entry into hitherto inaccessible fields of knowledge.

Ramjets are being developed largely because of their simplicity, expendability, and ability to develop high horsepower at supersonic speeds. Their direct peacetime application depends on how large a price we are willing to pay for rapidity of transportation. If we wish to emulate Puck in "Midsummer Night's Dream" and "put a girdle round about the world in forty minutes," then we shall probably use ramjets. Although the direct application of ramjets is problematical, I think there is no doubt that the knowledge and techniques being learned in their development will find considerable application. I have indicated that the problems in air flow, combustion, control of high-speed combustion, materials, and heat transfer are severe in ramjets, and their solution will advance the state of the art of high-speed combustion which is still fundamental in our whole technology.

In this lecture we have made a general survey of typical activities in the field of the development of guided missiles, indicating the urgency of the problems that have inspired this development and some of the technical material and methods at hand for the practical realization of these devices. It has been emphasized that rockets and guided missiles lie along the main line of the evolution of offensive and defensive weapons and are not chance mutations of immense technical interest but ephemeral practical importance. As long as the security of our peaceful institutions and way of life requires as its front line of protection a means of discouraging or defeating aggression by armed force, we must move along this main line of evolution. I would guess that centuries will elapse before we have developed a philosophy of life that will permit us to abandon this front line of the defense of civilization with a clear conscience. In the meantime we must face the fact that those responsible for our military security must be supplied with instruments that embody the latest in scientific knowledge and engineering

skill. Anything less is merely a snare and a delusion. Although we are only on the verge of the atomic era, we are in the midst of the age of jet propulsion, electronics, supersonic flight, high-speed mechanical computation and communication. The guided missile is one contribution to national defense that symbolizes the special advances of this age and synthesizes them into a combination that gives the speed, range, accuracy, and rapidity of control demanded by modern warfare.

The realistic thinker will not expect miracles or even rapid or revolutionary changes in military and technical thought and outlook from the development of guided missiles. He will remember that experience of 300 years has taught us to rely on evolutionary processes for positive and definite progress. It has taught us that the way to great achievements is by the step-by-step solution first of scientific problems and then of engineering ones. The nation that survives is the nation that keeps in the van of this march. Scientific principles now established indicate that satellite vehicles, interplanetary rockets, or full-scale push-button warfare are not at all fantastic. If, however, we conclude that "they are just around the corner" we ignore two fundamental facts: (1) That there is a long road of engineering evolution ahead that must be followed step by step before the art is advanced to a place where such devices can become the subject of serious thought and effort; (2) that expensive developments such as these are undertaken seriously only when military, economic, or other urgent necessity demands them. Thus, in this lecture we have traced the path from the unguided small rocket to the huge ballistic rocket (V-2), to the simpler guided missiles. Each step taken in perfecting these devices carries us further along the road to the realization of the long-range supersonic missile, the satellite rocket or the space ship, and wisdom dictates that we first exploit to the fullest extent unguided rockets, ballistic rockets, and fully guided missiles which have a big role to play now and in the future, and that by doing so we shall be furnished with knowledge and skill to attack the larger problems when the necessity arises.

Major J. R. Randolph Addresses Students

MAJOR J. R. Randolph, former editor of the JOURNAL OF THE AMERICAN ROCKET SOCIETY, on the Wednesday before the Christmas recess addressed a group of Pratt Institute (Brooklyn, N. Y.) students on the subject of rockets and space travel. Major Randolph made particular mention of the "electro-pult," an electrical starting device which he feels will eliminate the costly waste of fuel now required for the take-off of rockets. By means of the electro-pult and thousands of "orbiters," Major Randolph said, the establishment of a space station would be possible, which would offer unlimited possibilities for space patrol.

TORPEDO-PROPULSION SYSTEMS

By Frederick A. Maxfield

Head Physicist, Underwater Ordnance Branch, Bureau of Ordnance, Navy Department, Washington, D. C.

Present-day torpedoes are highly specialized pieces of machinery which have been designed to fulfill a specific function. The development of these weapons from the original Whitehead model to those of World War II has followed a slow course parallel with other developments in engineering, physics, and metallurgy.

In this paper some of the principal design objectives for effective torpedo-propulsion systems have been outlined and an attempt has been made to show how American torpedo development, particularly between World War I and World War II, has been guided by these requirements. Propulsion systems most used during World War II are described in some detail and compared with contemporary equipment developed by foreign nations. Finally, the present state of development of high-power-compact propulsion systems has been discussed and some mention has been made of the direction in which future developments appear to be headed.

DURING the early part of World War II one of the most effective weapons of the Germans, one which nearly prevented our active participation in the war in Europe, was the automobile torpedo used by the German U-boats to sink our freighters. Later this same weapon, as wielded by the Japanese, was largely responsible for the tragedy of Pearl Harbor. One consolation is that in our own hands similar torpedoes played a major role in effecting the defeat of the Japanese military forces.

As used in World War II, torpedoes were extremely efficient underwater missiles, designed to carry the greatest amount of explosive possible—within the limited available space—and designed to carry this charge to the target at the highest possible speed. To achieve this result it has been necessary to design engines and propulsion equipment as well as automatic control equipment which would fit into the smallest possible space and yet deliver the maximum possible power. Details of propulsion systems designed for this purpose and used in the war will be described later on. However in view of the almost complete lack of published information on torpedoes and their development, a slight digression to discuss briefly their origin and design requirements seems necessary.

Torpedo Development to World War II

Although various types of floating mines or ships laden with explosives

Presented at the Spring Meeting of the AMERICAN ROCKET SOCIETY, Mohican Hotel, New London, Conn., May 2, 1949.

have been used in military engagements since the days of antiquity, modern undersea warfare probably dates from 1771 when David Bushnell, while still a student at Yale College, discovered that a charge of gunpowder could be fired underwater. During the Revolutionary War he made several attempts to sink the British ships stationed in our harbors with underwater charges of this character. The earliest attempts were made by suspending kegs of gunpowder from floats and attempting to float these down against the enemy ships. Later because of the failure of these charges to produce significant damage, he created an underwater craft which was probably the first operating submarine, Fig. 1, and by means of it attempted to fasten an underwater charge to the flagship of the British Fleet in New York harbor. The expedition failed because Sergeant Ezra Lee, who manned the boat, was unable to penetrate the copper sheathing of the *Eagle* with the wood screw device provided for fastening the charge to the ship's bottom.

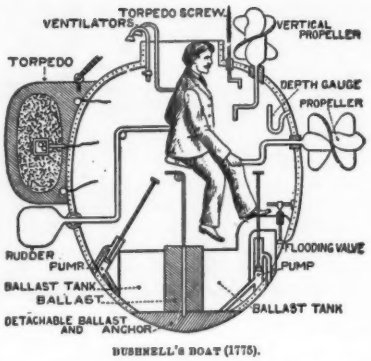


FIG. 1 BUSHNELL'S BOAT (1775)

Soon after the Revolution, Robert Fulton became interested in the design and use of underwater explosives and, because of lack of interest in this country, spent several years trying to interest both the French and the English in his torpedoes. The British, in particular, thought enough of his work to pay him £15,000 for his services. The weapons, although demonstrated successfully several times, were never used successfully in an offensive military operation.

Various other designs for underwater explosive weapons were made in the years up to the Civil War but none of these were sponsored by the government. During the Civil War, the Confederate government, principally because its fleet was inferior to that of the North, actively pursued the development of torpedoes and in spite of innumerable difficulties achieved considerable success with floating and spar torpedoes, sinking or damaging 22 Federal ships and losing only 6 of its own ships by these weapons. Fig. 2 shows a typical spar torpedo of this period. As can be seen, it consists of a charge mounted on the end of a long pole and projected ahead of a small high-speed steam launch. Seven knots was considered high speed.

Even during the Civil War, the importance of having a really mobile underwater weapon for offensive and defensive use was recognized. The spar torpedo was the first attempt to achieve this mobility. However it

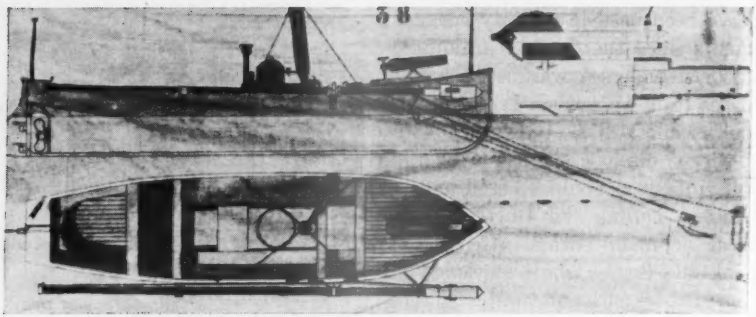


FIG. 2 CIVIL WAR SPAR TORPEDO

had many obvious disadvantages, the most important of which was that it could be operated with stealth only on dark moonless nights and once detected it could easily be stopped with gunfire. It was natural that in these circumstances someone would attempt to produce an entirely self-propelled submarine missile. Many attempts were made in the years that followed, but it is interesting to note that the first design was the most successful and until recently was the prototype of practically all torpedoes produced in this country and abroad. This torpedo is the one produced in 1866 by Robert Whitehead, who was at the time manager of the Stabilimento Tecnico Fiumano, an engineering concern established at Fiume, Italy, under English management some ten years before.

The original Whitehead torpedo was 14 in. in diam and 11 ft long. It weighed 300 lb and carried a charge of 18 lb of dynamite. Propulsion was provided by a two-cylinder V-type engine operated by compressed air. Constant speed was obtained by regulating the valve cut-off as the air pressure in the flask fell. The maximum air pressure used was 370 psi. This torpedo is reported to have attained a speed of 6 knots for 700 yards, although its reliable range on a straight course was probably considerably less. The torpedo apparently had no controls for steering in azimuth, its rudders being set empirically, and its depth controls were extremely rudimentary and uncertain. In the next two years Whitehead made several improvements, the most important of which was simply labeled "The Secret." This was an improved depth control which embodied a pendulum as well as a hydrostatic bellows so that the controls could be made sensitive both to depth and to torpedo attitude.

In the ensuing years the Whitehead torpedo was adopted by nearly all the countries of Europe, but the United States did not obtain a license to manufacture it until 1891. Torpedo design in this country was strongly influenced by Whitehead's design although many other systems of propulsion were investigated. The first fish torpedo produced in this country was built by the Naval Torpedo Station in Newport, R. I., in 1871. This

was two years after the establishment of the station and the torpedo was quite frankly a copy of Whitehead's design (see Fig. 3) although an attempt was made to improve on its performance. This torpedo had the following characteristics:

Diameter	15 in.
Length	12 ft 5 in.
Speed	6–8 mph
Range	300–400 yards
Explosive	70–90 lb of dynamite or guncotton

In the next 20 years, although little was done toward improving the Whitehead torpedo in this country, practically every other type of propulsion imaginable was tried out with varying degrees of success. The Harvey towed or Otter torpedo was perhaps the simplest. It was adopted for service use in 1869 and was used by the Russians in the Russo-Turkish War of 1877–1878. This torpedo was simply towed outboard from a ship in the manner of present-day paravanes. At about the same time John J. Lay at the Naval Torpedo Station started a series of experiments which, with those of his associates, extended over 20 years. These were all aimed at producing a torpedo which could be remotely controlled. All of these were either surface torpedoes, that is, they ran just awash, or were suspended from floats. Lay's first torpedo used carbonic acid gas to drive a gas engine and was steered by means of remotely controlled electromagnets which operated the valves of another gas engine. A later design (1880), the Lay-Haight, used a three-cylinder Brotherhood engine for propulsion. The fuel was again carbonic acid drawn in liquid form from a flask and expanded in outside tubes warmed by sea water. In 1883 tests were made using a mixture of sulphuric acid and lime to propel this torpedo. Speeds of 15 knots were attained. Fig. 4 shows the original Lay torpedo as it looked in 1892.

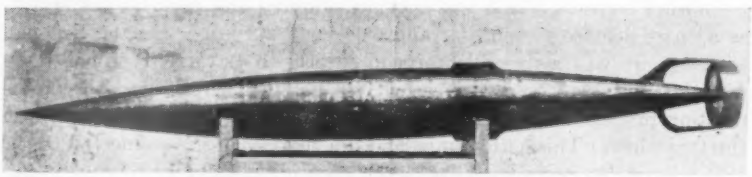


FIG. 3 "AUTOMOBILE" FISH TORPEDO (1871)

FIG. 4 LAY TORPEDO NO. 1

FIG. 5 CUNNINGHAM ROCKET TORPEDO

As a further improvement on the Lay torpedo, the Patrick torpedo was developed in 1886. This design provided for a float to support the torpedo about 3 ft below the surface. Better control was thus attained as well as less vulnerability to gunfire. This torpedo was supported from a 12-in.-diam, 41-ft-long float and was itself 36 ft long by 22 in. in diam. It was controlled by a wire cable 7000 ft in length. In tests it attained speeds of 19–22 mph.

Concurrently with the development of the various Lay torpedoes, Ericsson, designer of the *Monitor*, designed a torpedo which was propelled and steered by compressed air fed to it by an 800-ft rubber hose. Two models were built in 1873 and 1877 but the system proved impractical and was abandoned. Later Ericsson proposed a projectile torpedo to be fired from an underwater gun. One of these was apparently built and tested in 1881 and although the torpedo was $25^1/_2$ ft long and 16 in. in diam and weighed 1500 lb, speeds of approximately 60 knots were obtained to a range of 300 ft. Because of its poor accuracy and short range, it never passed the preliminary test stage.

Another torpedo, which was actually adopted and used by the British as a coast defense weapon for approximately 20 years, was the Brennan torpedo. It was a dirigible torpedo similar to Lay's but propelled by pulling from shore on two reels of 18-gage steel wire geared to contra-rotating propellers. The torpedo was steered by varying the tension on the two wires. This action unbalanced a rudder control connected to the two reels in the torpedo. The depth control was similar to that in the Whitehead torpedoes. A speed in excess of 20 knots for 3000 yards was claimed for this weapon.

Electric torpedoes also were investigated starting with the Foster torpedo in 1872. This torpedo, as well as the more successful Sims-Edison constructed in 1877, was controlled and powered from a shore station by means of a trailing wire. By 1887 development had progressed to the point where speeds of 10.2 knots to a range of two miles could be obtained. The torpedo was 28 ft long by 21 in. in diam and was supported by a copper

float filled with waterproofed cotton. This development was also abandoned because of the low speeds possible.

Starting with the Callender rocket torpedo in 1862, a number of designs of this type were tried out in the search for the most desirable propulsive means. The Weeks rocket torpedo tested in 1884 attained speeds of 23 to 45 knots for approximately 850 ft and the Cunningham, built in 1893, attained speeds nearly as great. The latter, although partially stabilized by helical fins (Fig. 5), was still quite inaccurate and unreliable in speed. These factors more than any other were responsible for the abandonment of this development.[1]

The most successful competitor of the Whitehead torpedo was the Howell torpedo developed in this country during the 1880's and used by some of our battleships until about 1898, when it was supplanted by the Whitehead torpedo.

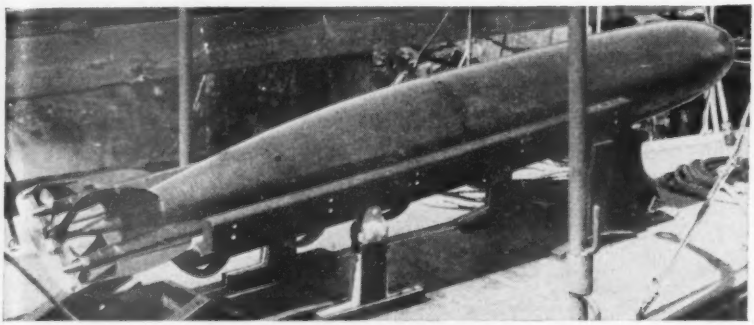


FIG. 6 HOWELL TORPEDO (1892)

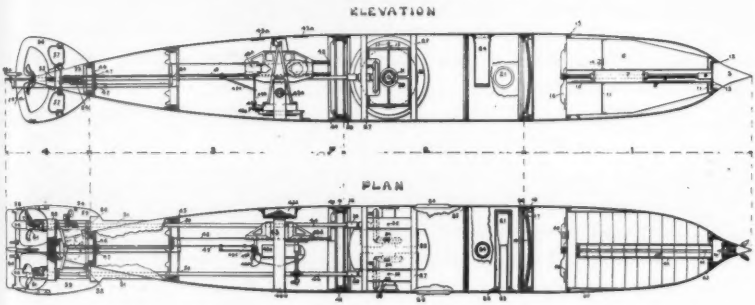


FIG. 7 HOWELL TORPEDO (VERTICAL AND HORIZONTAL PLANES)

[1] Mr. Cunningham, a New Bedford, Mass. shoemaker, took one of his rocket torpedoes home with him and on the 4th of July, 1897, touched it off in the road in front of his house as part of the celebration. It took off with a roar, narrowly missed several people, caused several runaway horses, and then smashed into a butcher shop and ended up in the ice box where it caused quite a fire.

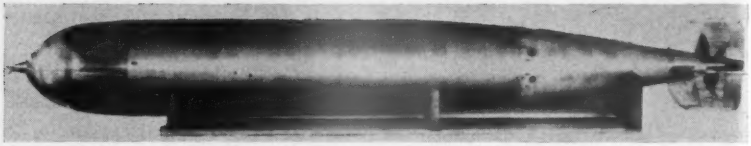


FIG. 8 WHITEHEAD TORPEDO, MARK 1 (1892)

The Howell torpedo received its power from a flywheel, prespun before launching. In the model of 1884, a 112-lb flywheel was mounted in a 14-in. torpedo whose total weight with 50 lb of explosive was only 300 lb. Later models used a 130-lb flywheel prespun to 10,000 rpm by an external steam engine mounted on the torpedo tube. As shown in Figs. 6 and 7, propulsion was obtained by means of two propellers whose parallel shafts were driven by bevel gears from the two sides of the flywheel. Constant speed was obtained by means of variable pitch propellers controlled by the falling speed of the flywheel. With this torpedo, speeds of 25 knots were obtained to 400 yards and over-runs to 800 yards were obtained as the speed fell.

The gyroscopic action of the flywheel in this torpedo was used to achieve good directional stability. Deflections from course would induce heel and influence a pendulum mounted on a fore and aft axis and so coupled to the rudders as to correct the course of the torpedo. The depth-keeping characteristics of the Howell torpedo, however, were not good.

In 1892, probably inspired by the successful use of a Whitehead torpedo against the Chilean insurgent battleship *Blanco Encalada*, or by the fact that one of the Maxims had been retained as a consultant by the E. W. Bliss Company, the United States completed negotiations with the Whitehead Company for the manufacture of its torpedoes in this country by the E. W. Bliss Company. Fig. 8 shows one of the first of these torpedoes. This 18-in. missile, as all previous Whitehead torpedoes, was propelled by compressed air through a three-cylinder reciprocating engine. However improvements had been made and this weapon was capable of 30 knots for 800 yards. The Mark 1 Whitehead was the first to carry a steering gyroscope, the so-called Obry gyroscope.

The Mark 2 and Mark 3 Whitehead torpedoes embodied slight changes in design but they were all "cold-running" torpedoes.

The advantages of hot gases in increasing the efficiency of these engines (or the disadvantage of cold gases) was evidently well understood, for about 1904 a scheme was introduced for heating the air in the air flask by burning in it a spray of liquid fuel which was ignited by a cartridge. This was soon followed by a design using an outside heater or combustion pot to heat the air before it entered the engine. The Mark 5 Whitehead torpedo was the first to carry this heater. The next step was to spray water also into the combustion pot in order to prevent excessive temperatures. The resultant

steam further increased the efficiency of the engine and led to the device being called a "steam" torpedo although only a fraction of the gas used in the engine was steam.

Although the British had experimented with a torpedo powered by a Parsons turbine in 1899, it remained for the E. W. Bliss Company to produce the first successful turbine-driven torpedo which became the Mark 1 Bliss-Leavitt torpedo in 1904. This was a two-stage Curtis turbine which was operated by the hot gases from the combustion pot. Figs. 9 and 10 show approximately contemporary engines as used in the Mark 5 Whitehead and Mark 4 Bliss-Leavitt torpedoes. Except for minor changes such as changing the axis of rotation from horizontal to vertical, this is essentially the same power plant that has been used in all our torpedoes up through World War II. Incidentally, until very recently the United States Navy was the only one which used turbines in its torpedoes, all others continuing to use various forms of the Whitehead torpedo or the Schwartzkopf, the modified design developed in Germany from the Whitehead.

FIG. 9 FOUR-CYLINDER ENGINE USED IN MARK 5 WHITEHEAD TORPEDO

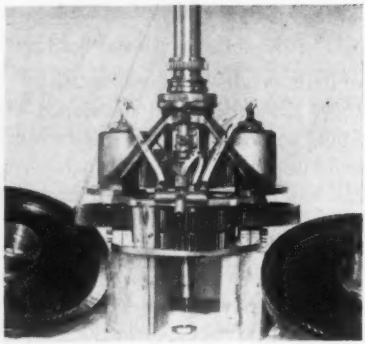


FIG. 10 BALANCED TURBINE USED IN MARK 4 BLISS-LEAVITT TORPEDO (1910)

FIG. 11 BLISS-LEAVITT TORPEDO, MARK 3 (1911)

FIG. 12 TORPEDO, MARK 14, MOD 3A

The Mark 1 torpedo, which was designed for battleships and cruisers, was soon followed by a longer range Mark 2 and Mark 3, and by the submarine torpedo Mark 4. Fig. 11 shows the Mark 3. The Mark 6 introduced in 1911 was the first to utilize the horizontal turbine wheel, and the Mark 8 of 1913 was the first 21-in. diam, 21-ft long torpedo. Further developments culminated in our World War II Mark 14, Mod 3A torpedo for submarine use and the Mark 15 for destroyer use. These are shown in Figs. 12 and 13.

During World War I, work was resumed at the Sperry Gyroscope Company on an electric torpedo. This development was taken over by the Naval Torpedo Station in 1918 and carried on intermittently until 1931 when the work was finally stopped. The principal difficulty with this development seems to have been the procurement of a satisfactory battery

FIG. 13 TORPEDO, MARK 15

of light weight and high capacity. The Germans had apparently mastered these difficulties and developed an electric torpedo with a speed of 27 knots and range of 1500 meters by the end of the war in 1917. All of these produced were destroyed in November, 1918, to prevent their falling into the hands of the Allies. The design was apparently retained by the Germans, and at the start of World War II they commenced using them effectively. Although these torpedoes were in general slower and of shorter range than the engine-driven torpedoes, they had the advantage of being entirely wakeless and hence completely invisible until they struck their target. Soon after the start of World War II a few of these torpedoes were captured and our Mark 18 torpedo was built as an almost identical copy.

Torpedo Design Criteria

Let us examine for a moment the design criteria which are involved in a satisfactory present-day torpedo and then we can see to what degree the weapons used during World War II fulfilled these various requirements. In the first place the structure of the torpedo is determined by the use to which it is put. Thus, an aircraft torpedo will require a considerably stronger body than a submarine- or even a surface-launched torpedo because of the severe stresses induced during water entry. Since the greatest speed and range possible is always wanted, the size of the torpedo is important. The size is limited by the type of craft which will carry the missile and by the fact that the larger the torpedo is, the greater will be the hydrodynamic drag, consequently the greater will be the power required for a given speed.

The United States Navy adopted the following dimensions for its World War II weapons:

Aircraft torpedoes (Mark 13)	22.4 in. diam; 161 in. long
Destroyer torpedoes (Mark 15)	21 in. diam; 288 in. long
Submarine torpedoes (Mark 14 and 18)	21 in. diam; 246 in. long

Having determined the size of the torpedo, its weight is also roughly determined, since the negative buoyancy cannot exceed about 35 per cent of the total buoyancy in torpedoes of this length without difficulty being encountered in the controls. The available weight and space must then be apportioned between the engine, its fuel and oxidant, the control equipment, and the explosive charge. We see then that if speed and range are to be increased the most efficient engines possible must be developed. The problem is very similar to that encountered in aircraft propulsion design with two exceptions. First, conventional torpedo engines cannot take advantage of the surrounding medium to provide an oxidant for the fuel carried as can be done with aircraft. But opposed to this is the second major difference, namely, that the average life of a torpedo engine can be made quite short and consequently it may be heavily overloaded. The torpedo is not, however, a one-shot device even though it can only be used once in combat. Although each run may be short, a torpedo engine must usually be able to withstand a number of runs during its proving tests and while being used as a training device.

There are a number of other characteristics that must also be taken into account in a torpedo design if it is to be a successful present-day weapon. Thus, the torpedo should start quickly and deliver full power usually within less than a second after firing or hitting the water. It should be easy to maintain under service conditions. It should resist corrosion or malfunctioning caused by either long storage, intermittent use, or operation in sea water, and it should be as quiet and as nearly wakeless as possible in order to avoid detection when fired from submarines. This last means that the exhaust products should be soluble in water.

To satisfy these requirements practically every type of propulsion system ever proposed has at one time or another been tried in a torpedo. As we have seen, some of the first torpedoes used external propulsive means, and we had the projectile torpedo and the remotely powered (so-called locomotive) torpedoes among which we can also classify the Howell torpedo, since it received its energy from an engine attached to the torpedo tube. Then during the early years of the development of reciprocating engines we had these, followed by turbine propulsion and electric propulsion when they were developed. Finally we have had rocket propulsion and even some attempts to produce other types of jet propulsion similar to the ramjet and pulsejet used in air-flight missiles. Without exception, the torpedoes of all belligerents during World War II were powered by either reciprocating

FIG. 14 CROSS SECTION OF TORPEDO, MARK 14

engine, turbine, or electric motor. Differences that appeared in these torpedoes were due to differences in design and efficiency of these various engines, or due to differences in the type of fuel used.

World War II U. S. Torpedoes

The United States Navy torpedoes, Mark 13, 14, and 15 were essentially alike, differing, as noted above, principally in the size of the body in which the engine was enclosed. All were turbine driven and used alcohol and compressed air for the fuel and oxidant. All also used fresh water as a diluent in the combustion chamber. Because of their differences in size, the amount of air and fuel carried varied and consequently the ranges and speeds differed, the Mark 13 (aircraft) torpedo having a speed of 33.5 knots for 5500 yards, the Mark 14, Mod 3A (submarine) torpedo having a speed of 46 knots for 4500 yards, or 32 knots for 9000 yards, and the Mark 15 (destroyer) torpedo having speeds of 45 knots, 33.5 knots, and 26.5 knots for ranges of 6000, 10,000, and 15,000 yards, respectively. The propulsion system and controls in all these torpedoes were essentially the same.

Fig. 14 shows a cross-section picture of the torpedo, Mark 14 Mod 3A. The operation of the torpedo is shown schematically in Fig. 15. The following description of the operation of this torpedo is quoted from the manual:

"High-pressure air (2800 psi) is stored in the air flask. It is fed through the stop and charging valve, through the preheater, then through a small orifice in the starting valve of the starting and reducing valve group, and

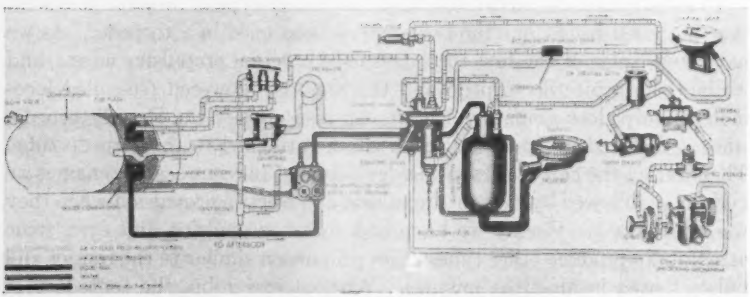


FIG. 15 SCHEMATIC DIAGRAM, TORPEDO, MARK 14

to the piston of the starting gear. The air is held under high pressure between the air flask and the starting-gear piston until the torpedo is launched.

"As the torpedo is fired, the starting lever is thrown aft by the tripping latch in the tube, and this action lifts the starting piston off its seat. As the starting piston is lifted, the high-pressure air banked up over the starting valve is released, thereby allowing the starting valve to lift. As the starting valve lifts, the air passes to all the operating mechanisms of the torpedo.

"Part of the high-pressure air is diverted to the gyro spinning mechanism, and part to the control chamber of the reducing valve. The bulk of the high-pressure air entering the reducing-valve chamber passes through the reducing valve, where the air is reduced from flask pressure to approximately 450 psi. This reduced-pressure air is then distributed by three branches: (*a*) To the air checks; (*b*) through the restriction valve to the combustion flask; and (*c*) to the igniter.

"From the air checks, the low-pressure air flows to the water compartment and to the fuel flask, forcing the water and fuel through pipes to the water and fuel strainers and check valves. The fuel and water then pass through their respective restrictions in the restriction valve to the fuel and water sprays in the combustion flask. The main supply of the reduced-pressure air passes through the air restriction in the restriction valve and to the combustion flask.

"The reduced-pressure air also fires the igniter, which ignites the fuel in the combustion flask, where the combination of fuel, air, and water is converted into gases and steam at a high temperature and fed through a pipe to the nozzles of the turbines, furnishing the power for propelling the torpedo.

"Air passes from the top of the combustion flask and from the control valve to the air-strainer body. From the air-strainer body, this air flows through two branches. One branch leads to the steering engine and through the gyro reducer to the gyro (which is inside the gyro pot) where it sustains the spin of the gyro. The other branch leads from the air-strainer body to the depth engine."

As mentioned above, the United States Navy torpedo, Mark 18, was patterned after the German electric torpedo. Its development was due to the combined efforts of the Naval Torpedo Station at Newport and the Westinghouse Electric Corporation in the first months of the war. In fact, in less than 10 months after the first German torpedo was received at the Torpedo Station, and just six months after a letter of intent was issued authorizing the manufacture of these torpedoes, the initial lot of production torpedoes was received from Westinghouse. Considering the years that had been required for the development of every other torpedo, this was a really phenomenal accomplishment.

Fig. 16 shows a cutaway view of this torpedo. From this it can be

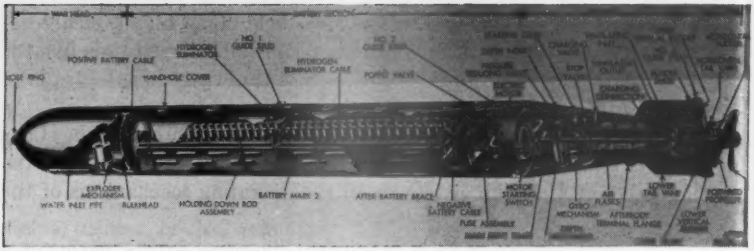


FIG. 16 CUTAWAY VIEW OF TORPEDO, MARK 18

seen that the electric power is used to drive the main motor only. The gyro and all auxiliary controls are driven from high-pressure air in exactly the same manner as in the torpedo, Mark 14. The battery used was a conventional lead-acid type weighing 1220 lb and rated at 4.56 kwhr. This torpedo was rated at 29 knots with a range of 4000 yards. The German torpedo, Type G7e, although the same diameter, was somewhat longer (284 in.) and carried a larger battery. Its range, consequently, was 5500 yards at 30 knots.

World War II Foreign Torpedoes

At the start of World War II, the standard American, British, and German engine-driven torpedoes, as shown in Table 1, had very nearly the same

TABLE 1 AMERICAN AND FOREIGN TORPEDOES

	American	British	German
Type	Mk. 14-3A	21-in. Mk. 4	G7a
Range, yards	4500	5000	6600
Speed, knots	46	40	44
Engine type	turbine	4-cyl radial (wet heater)	4-cyl radial
Fuel	alcohol	kerosene	decalin
Fuel wt, lb	28	15	36
Oxidant	air	air	air
Oxidant wt, lb	256	262	350
Diluent	water	water	water
Diluent wt, lb	83	99	125
Total expendables, lb	367	376	511
Expendables used, lb	322	233	423
Regulator pressure, psi	490	700	700 (?)
Shaft horsepower	340	220	303
Engine and transmission wt, lb	326	....	....
Container wt, lb	1062	....	....
Total wt, lb	3185	3182	3385
Engine wt per hp	0.96	....	....
Expendables carried per hphr	22.2	27.8	22.6
Expendables used per hphr	19.5	17.3	18.7

characteristics, although their power plants differed somewhat. By some standards the power plants used in these torpedoes might be considered very efficient since the ratio of engine weight to horsepower produced is close to one in all three cases. Because these torpedoes must carry their oxidant and diluent with them in the form of compressed air and water, the total weight of fuel containers is high and the weight of expendables used per hphr is also high. As a result the range and speed obtainable with these torpedoes was limited to approximately 5000 yards at 45 knots in each case. Without radical changes in engine design, longer ranges or higher speeds could only be obtained by increasing the length of the torpedo as was done in the case of the American torpedo, Mark 15.

One obvious way to decrease the load of expendables which must be carried in the torpedo is to use sea water as the diluent. This method immediately introduces serious maintenance problems caused by corrosion and the possibility of troublesome salt deposits in the combustion chamber and engine which may interfere with and prevent long-range operation and which necessitates a complete engine overhaul after each run. Nevertheless sea-water injection was adopted for the German Stein-Wal torpedo and for Japanese torpedoes and produced a marked increase in efficiency.

A second method is to convert the so-called "wet-heater" reciprocating engine to an internal-combustion engine. This scheme was adopted by the British for their B-cycle engine with a considerable increase in efficiency.

A third and more significant improvement in engine efficiency can be obtained by eliminating the large air flask and utilizing a liquid oxidizer in place of air. Because of the high pressure air flasks, approximately 4 lb of container weight are required for each pound of gas carried, while only 1 lb of container weight is required for each pound of liquid carried. This saving in weight can then be converted to increased fuel capacity and to further increase the range or power output. The Japanese Type 93 torpedo, which had a range of 20,000 yards at 48 knots, used liquid oxygen and sea water in its two-cylinder engine and was able to achieve an efficiency such that the engine used only about 7.7 lb of expendables per hphr.[2]

Liquid oxygen introduces many problems of storage and maintenance and for this reason is not highly desirable. The Germans met the problem by using 80 per cent hydrogen peroxide for the oxidant. With this material and fresh water diluent, as Table 2 shows, they reduced the expendable rate in their turbine-driven Stein-Butt torpedo to approximately 17.7 lb per hphr and increased the range at 45 knots to over 8000 yards and by converting to sea water as the diluent the Stein-Wal was made to operate on 8.5 lb of expendables per hphr. Both the Stein-Butt and the Stein-Wal used essentially the same turbine engine which was adopted to replace

[2] The sea water used is, of course, not included in these expendable rates.

TABLE 2 FOREIGN TORPEDOES

	British	German	German
Type	21-in. Mk. 8	Stein-Butt	Stein-Wal
Range, yards	5000	8750	24,000
Speed, knots	45.5	45	45
Engine type	4-cyl radial B-cycle	turbine	turbine
Fuel	kerosene	decalin	decalin
Fuel wt, lb	30	37	110
Oxidant	air	H_2O_2	H_2O_2
Oxidant wt, lb	241	284	814
Diluent	none	water	sea water
Diluent wt, lb	....	378	.....
Other fluids	none	air and catalyst	air, catalyst, and fresh water
Other fluids wt, lb	....	59	106
Total expendables, lb	271	758	1029
Expendables used, lb	159	725	1000
Regular pressure, psi	700	700 (?)	700 (?)
Shaft horsepower	320	435	435
Container wt, lb	....	900	950
Total wt, lb	3452	3696	3960
Expendables carried per hphr	15.4	18.5	8.8
Expendables used per hphr	9.0	17.7	8.5

the older reciprocating engine during the early part of World War II. The Stein-Wal torpedo had a range of 23,000 yards at 45 knots which was a considerable improvement over the G7a. The development of this torpedo was just being completed at the end of the war and none saw service use.

It may be noted that the expendable rate per hphr for the Stein-Wal torpedo is not as low as that for the Japanese Type 93. This is characteristic of turbine propulsion when compared with internal-combustion type engines. Early in the war the Germans switched from a reciprocating engine drive to a turbine drive when they started to use hydrogen peroxide as an oxidant, in order to eliminate oil from the wake. By changing to hydrogen peroxide the nonsoluble gases in the exhaust were practically eliminated and these torpedoes were essentially wakeless. It was for this reason more than any other, that the Germans concentrated their development effort during the war on these torpedoes.

The engine that was finally designed after a series of experiments with several types of turbines, combustion chambers, fluid ratios, and mechanical arrangements was an extremely compact unit as shown in Figs. 17 and 18. The housing for the engine as shown in Fig. 17 constituted a section of the torpedo shell and was welded together from ordinary pressed steel sheets. All connections to fluid containers were made by easily reached

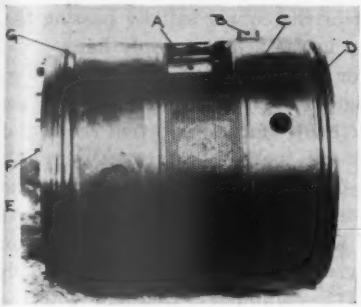


FIG. 17 ENGINE COMPARTMENT GERMAN G7UT TORPEDO

(*A*—recess for starting valve; *B*—guide stud; *C*—exhaust mantle; *D*—flange for "K" joint, forward end; *E*—slot for loading strap; *F*—bulkhead studs; and *G*—flange for "K" joint, after end)

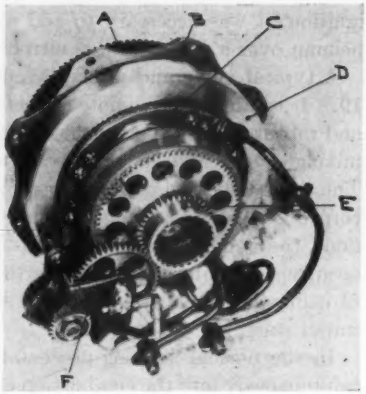


FIG. 18 TURBINE AND GEAR TRAIN, GERMAN G7UT TORPEDO

(*A*—turbine wheel; *B*—engine support; *C*—after-support for double gears; *D*—flywheel; *E*—propeller shaft coupling; and *F*—oil pump)

couplings at the forward face of this compartment. The turbine, which was designed for 500 hp and 30,000 rpm, was machined from a solid steel disk by means of a special machine developed by the firm of Askania, Berlin. Other revolutionary features included a cardan gear on the driving shaft which, with the internally toothed flywheel ring, revolved in the reverse direction to the turbine and prevented initial roll. Another unique feature was the scheme for conducting the exhaust directly from the turbine through the perforated shell of the torpedo into the sea, rather than through the propeller shaft as in previous torpedoes. Although this type of skin exhaust might be expected to interfere with the control surfaces and affect the stability of the missile, tests showed no effect.

The Stein-Wal was a so-called three-fluid torpedo, in which all fluids were pumped and only enough air and fresh water were carried to provide for starting. Actually since the catalyst was also fluid it should be called a four-fluid process. The catalyst used was called helman and consisted of 80 per cent hydrazine hydrate and 20 per cent ethyl alcohol with 0.5 gram per liter of potassium copper cyanate ($K_2Cu(CN)_3$) added to assist in ignition. Combustion was started by mixing helman with the fuel (decalin) and ingolin (hydrogen peroxide) in the combustion chamber. After combustion had been started, the supply of helman was cut off and further decomposition of hydrogen peroxide was obtained thermally. Because of the difficulty experienced in storing helman for long periods when it contained as much copper salt as was required for spontaneous

ignition, it was necessary to add most of the copper salt by passing the helman over a salt cartridge introduced in the helman supply line.

A typical valve and piping layout for these torpedoes is shown in Fig. 19. It is interesting to note in this diagram the liberal use of check valves and rupture disks (Sperrhaut) which were introduced to prevent accidental mixing of the hydrogen peroxide with the fuel and catalyst (hydralin). The cams indicated at the upper right-hand corner were used to start the torpedo. They also acted to cut off the flow of hydrogen peroxide and flood the combustion chamber if the torpedo broached. After such an occurrence, combustion was restarted by again introducing a certain amount of helman and hydrogen peroxide into the combustion chamber as in the initial start.

In the normal starting process, helman and decalin were introduced simultaneously into the combustion chamber through the same nozzle prior to the introduction of hydrogen peroxide. Experience showed that if this was not done and the peroxide reached the combustion chamber first, an explosion would occur due to the sudden decomposition of liquid peroxide. If, however, the helman was introduced first, there would be no explosion. The tank of helman was equipped with a stronger check valve than the fuel tank so that, after combustion started and a back pressure was developed in the lines leading to the combustion chamber, the flow of helman would stop while the flow of the other liquids would continue. In case of a broach, the valve arrangement provides for dumping the hydrogen peroxide into the sea and flooding the combustion chamber with water.

Hydrogen peroxide is in many ways an ideal oxidant since it gives up considerable heat during decomposition, its decomposition products are just oxygen and water, and in the presence of a suitable catalyst, decomposition occurs smoothly and rapidly. Some precautions are necessary in handling the material since it decomposes rapidly in the presence of most organic compounds and consequently must be kept free from all but minute amounts of impurities. It is sorted best in pure (99.6 per cent) aluminum containers.

Future Developments

Further improvement in engine efficiency may be possible by an increase in temperature of the gases used to drive the engine, but the increase will be small. Appreciable increases in efficiency will only be possible through an improvement in the fuels, and since practically all ordinary fuel-oxidant diluent combinations give essentially the same performance, this will only come about with the development of new fuels. One possibility is the use of water-reactive fuels, that is, fuels which react directly with sea water and yield a high heat output.

Another possibility for increasing the power-plant energy concentration in a torpedo in order to achieve higher speed, longer range, or smaller size

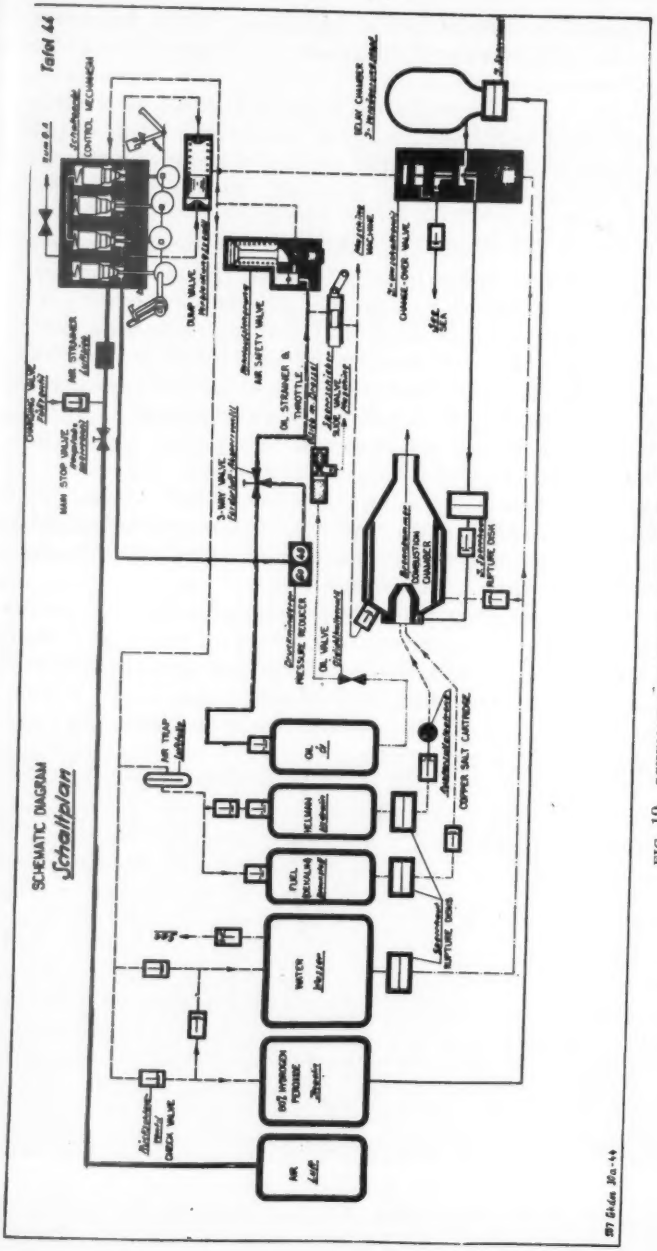


FIG. 19 SCHEMATIC DIAGRAM, GERMAN G7UT TORPEDO

is to use an entirely different type of propulsion. In the fifty years preceding the end of World War II, practically all the development effort by all nations was concentrated on the reciprocating engine, turbine, and electric-motor power plants with the result that a high degree of perfection has been obtained with these systems of propulsion. In the early years of its development a number of other systems of propulsion were investigated for torpedoes and ultimately discarded. Perhaps we ought to look again at some of these.

Just as in the case of air-borne vehicles, higher speeds have been obtained by the use of rocket, turbojet, pulsejet, and ramjet engines, and the most promising engine for a high-speed torpedo now appears to be some type of jet engine. Solid- or liquid-fuel rocket engines do not appear to be the answer. Although very high speeds can be obtained in particular applications, the efficiency of a rocket engine is low and consequently the range is short. No propellant such as oxygen or hydrogen peroxide and alcohol or nitromethane is outstanding in performance. All the fuels or fuel combinations seem to have essentially the same work output per lb of propellant, and the value of this is less than can be obtained with conventional engines in long-range torpedoes. The rocket engine, however, can be used effectively where only short ranges at high speed are required and where wakelessness is not a factor.

The turbojet, pulsejet, and ramjet adapted to underwater propulsion are possibilities for future development. Perhaps with one of these we will be able to obtain a power plant sufficiently compact and powerful to give us a really high-speed long-range weapon.

In conclusion, it should be pointed out that in addition to the problems of torpedo propulsion, the development of which has been briefly outlined in the preceding paragraphs, there are other serious problems associated with the development of modern torpedoes. These concern the design of suitable hydrodynamic shapes and control surfaces and the design of effective automatic control elements and servomechanisms for torpedoes. These are fully as important as the propulsion system in the development of a successful torpedo. The discussion of these subjects, however, will have to be postponed until another time.

The author is indebted to many sources for the information that appears in this paper and wishes to make proper acknowledgment to them. However, most of the sources are not available for general reference and only one comprehensive reference[3] on torpedo development appears to have been published in English in the past half-century.

[3] "Development of the Torpedo," by Comdr. Peter Bethell, R.N., a series of articles published in *Engineering* between May 25, 1945, and March 15, 1946.

THE FOURTH ANNUAL CONVENTION OF THE AMERICAN ROCKET SOCIETY

THE FOURTH Annual Convention of the American Rocket Society was held, in conjunction with The American Society of Mechanical Engineers, at the Hotel Statler, New York, N. Y., Nov. 27–Dec. 2, 1949. From the standpoint of registration and of the great interest in the Society expressed by members and guests, the Convention was a greater success than it was in 1948.

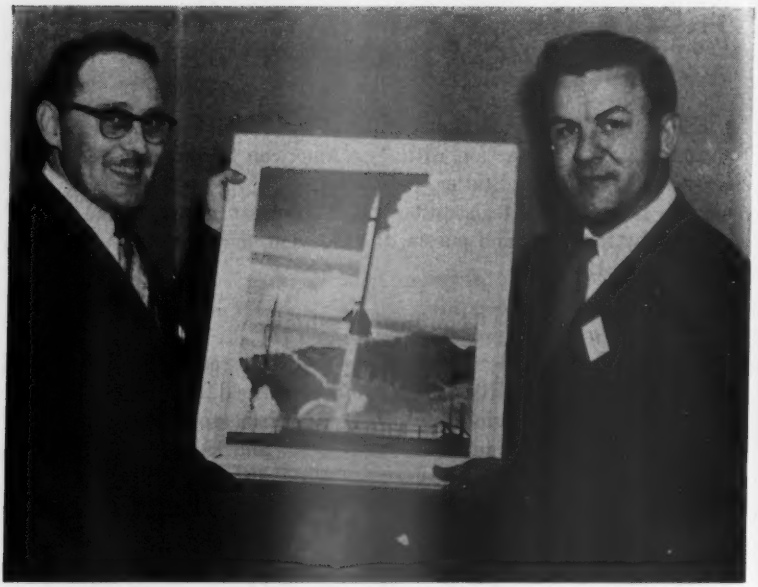
Technical Sessions

The American Rocket Society presented three technical sessions this year instead of the usual two. Martin Summerfield, editor, Aeronautical Publication Program, Princeton University, Princeton, N. J., discussed "Fundamental Problems in Rocket Research," and H. S. Tsien and Luigi Crocco, Robert H. Goddard professors from California Institute of Technology, Pasadena, Calif., and Princeton University, respectively, presented a complete report on activities of the Daniel and Florence Guggenheim Jet Propulsion Centers. G. P. Sutton, supervisor, Aerophysics Laboratory, North American Aviation, Downey, Calif., presented a paper on "Performance Parameters for Several Applications of Rocket Power Plants."

On Friday, Dec. 2, the American Rocket Society presented a session on fuels in which Noah S. Davis, Ralph Bloom, and Samuel D. Levine, project supervisors, Buffalo Electro Chemical Company, Buffalo,

AT THE HONORS NIGHT DINNER

(*Left to right:* C. N. Hickman, Mrs. R. H. Goddard, Admiral C. M. Bolster and Dan A. Kimball)



LOVELL LAWRENCE, JR., PRESIDENT, REACTION MOTORS, CONGRATULATES WILLIAM C. HOUSE OF THE AEROJET ENGINEERING CORPORATION ON HIS PAINTING WHICH WAS EXHIBITED DURING THE NATIONAL CONVENTION

N. Y., discussed "Hydrogen Peroxide as a Rocket Fuel"; Douglas H. Ross, Solvay Process Division, Allied Chemical and Dye Corporation, New York, N. Y., presented a paper on "Nitrogen Tetroxide as an Oxidizer in Rocket Propulsion," and G. E. Simpson, Linde Air Products, Inc., New York, N. Y., discussed "The Handling of Liquid Oxygen."

Every session was well attended and the discussions following the papers were particularly interesting.

Honors Night Dinner

For the first time the American Rocket Society held its own Honors Night Dinner. Previously the Society cosponsored a dinner with some division of the ASME. The Honors Night Dinner was a complete success in every way.

The annual presentation of the three American Rocket Society awards was made by William L. Gore, who acted as toastmaster. The Robert H. Goddard Memorial Award was presented to Admiral C. M. Bolster, assistant chief for research and development, Bureau of Aeronautics; the C. N. Hickman Award was presented to James A. Van Allen, director, upper atmosphere research, Applied Physics Laboratory; and the Ameri-

can Rocket Society Student Award was made to Leon Cooper of the College of the City of New York, New York, N. Y.

The speaker of the evening was Dan A. Kimball, Under Secretary of the Navy, who talked on "The Complexities of Peace." Mr. Kimball's speech was extremely interesting and commanded much attention from the press as well as from those attending the dinner.

The attention given to all of the American Rocket Society activities at this Convention by the press is a strong indication of the growth of the importance of the Society.

Election of Officers

The casting of the mail ballots for the annual election of officers for the year 1950 resulted in the election of the following officers: President, William L. Gore; Vice-President, H. R. J. Grosch. Directors for a term of three years beginning January, 1950: H. S. Tsien, Daniel and Florence Guggenheim Jet Propulsion Center, California Institute of Technology, Pasadena, Calif.; Frank Parker, director, "Project Squid," Princeton University, Princeton, N. J.; and C. W. Chillson, chief engineer, Curtiss Wright Corporation, Propeller Division, Caldwell, N. J.

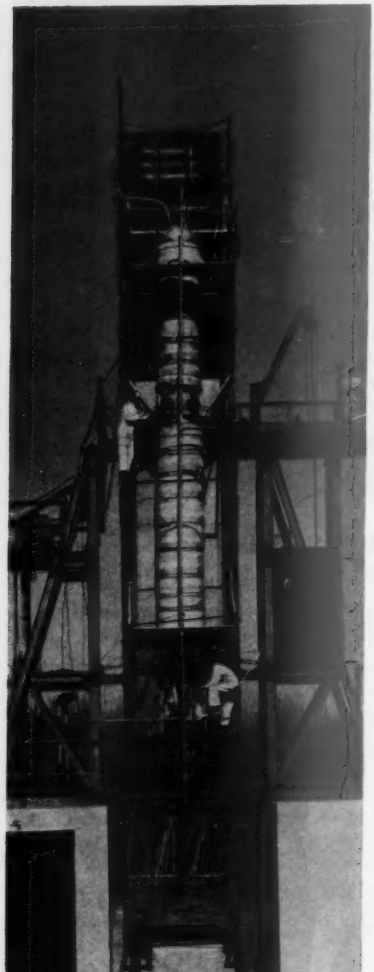
New ARS Corporate Member

CURTISS Wright Corporation, Propeller Division, Caldwell, N. J., has just become a corporate member of the American Rocket

DAN A. KIMBALL, UNDER SECRETARY OF THE NAVY, SPEAKS AT THE HONORS NIGHT DINNER

JAMES A. VAN ALLEN, WILLIAM L. GORE, AND C. N. HICKMAN DISCUSS ARS AFFAIRS AT THE HONOR NIGHT DINNER

Society. C. W. Chillson, chief engineer, was recently elected to a three-year term on the Board of Directors. Other corporate members are Reaction Motors, Inc., Aerojet Engineering Corporation, United Aircraft Corporation, Laurance S. Rockefeller, Thiokol Corporation, and Haynes Stellite Corporation. Affiliate corporate memberships in the American Rocket Society are held by Glenn L. Martin Company, Sealol Corporation and Louis J. Curran.



ENGINEERS PREPARE TO TEST-RUN ROCKET ENGINE IN NAVY VIKING SUPERSONIC GUIDED MISSILE AT REACTION MOTORS EXPERIMENTAL STAND AT LAKE DENMARK, N. J.

Reaction Motors, Inc., Holds Open House

ON Dec. 6, 1949, Reaction Motors, Inc., held ceremonies marking the formal opening of its new manufacturing plant and administrative office at Rockaway, N. J. For the last several years, the company has occupied facilities at Lake Denmark, N. J., which is approximately five miles from its new location in Rockaway. It will continue to operate these facilities for its research laboratories, engineering department, and testing activities.

Reaction Motors, Inc., has run up an impressive record of research and development, and during the last two years has propelled the Bell X-1, as well as the Douglas "Skyrocket," through the sonic barrier. It has also produced rocket engines for the Martin "Viking" missile and the Consolidated MX-774 missile.

Among those attending the ceremonies, in addition to many representatives of the Army and representatives of the aviation industry, were: Rear Admiral Lloyd Harrison, assistant chief, Design and Engineering, Bureau of Aeronautics; Rear Admiral C. M. Bolster, assist-

ant chief, Research Development, Bureau of Aeronautics; Admiral D. Royce, Bureau of Aeronautics general representative, Eastern District, Navy Department; Laurance S. Rockefeller; Brigadier General Arthur Thomas, Commander, New York Air Force Procurement Field Office; Col. J. W. Sessums, Jr., deputy chief, Research and Development, Air Materiel Command, Wright Field; Col. C. R. Dutton, representing The Assistant Secretary of the Army, and Col. J. P. Harris, Commanding Officer, Picatinny Arsenal, Dover, N. J.

Guggenheim Jet Propulsion Fellowships Available

SIX $2000 Daniel and Florence Guggenheim Jet Propulsion Fellowships are being offered to qualified applicants for advanced study in the field of rocket and jet-propulsion engineering. Three of the fellowships are for postgraduate study at Princeton University, Princeton, N. J., and three at California Institute of Technology, Pasadena, Calif., at the Jet Propulsion Centers established in 1948.

The Fellowships are open to qualified college graduates with suitable engineering or scientific undergraduate preparation. Candidates must have outstanding technical ability, deep interest in rockets and jet propulsion, and demonstrated leadership qualities.

Applications are being accepted now at the two institutions for fellowships beginning in the fall of 1950. They are normally granted for two years at a stipend of $2000 per year.

Posters, descriptive pamphlets, and application blanks have been distributed to colleges and universities, industries engaged in rocket and jet-propulsion work, government and service laboratories, and technical societies. The Secretary of the American Rocket Society will be glad to send additional information to anyone interested.

Reprints Available

"Instruction and Research at the Daniel and Florence Guggenheim Jet Propulsion Center at California Institute of Technology," by Hsue-Shen Tsien.

"Instruction and Research at the Daniel and Florence Guggenheim Jet Propulsion Center at Princeton University," by Luigi Crocco.

"Nitrogen Tetroxide as an Oxidizer in Rocket Propulsion," by Douglas H. Ross.

"The Handling of Liquid Oxygen," by G. E. Simpson.

"Optimization Studies of Rocket Power Plants," by G. P. Sutton.

"Fundamental Problems in Rocket Research," by Martin Summerfield.

Order from Secretary, ARS, 29 West 39th Street, New York 18, N. Y. Price is 25 cents per paper.

ARS News

Southern California Section

SEVERAL members of the Southern California Section came to New York to attend the Fourth Annual Convention of the American Rocket Society. G. P. Sutton, president, ARS Southern California Section, presented a paper at one of the technical sessions which was well received. An indication of the interest in it is the increasing demand for reprints which have been coming into the Secretary's office.

William C. House and David Young were also in New York, and Mr. House painted two rocket pictures which were prominently displayed at the Convention.

New York Section

THE casting of the mail ballots of the New York Section for the year ending January, 1951, resulted in election of the following directors for a term of three years: W. E. Kuhn, The Texas Company; Paul F. Winternitz, Reaction Motors, Inc.; and R. Shainin, Curtiss Wright Corporation.

ON January 20 the New York Section held its regular monthly meeting at the Engineering Societies Building. A group of 225 people listened and watched attentively while D. R. Bellman, Aeronautical research scientist, National Advisory Committee for Aeronautics, presented a discussion of "A Photographic Method for Studying Rocket Combustion."

The talk was illustrated by slides and a movie, and Mr. Bellman, in addition, had a small exhibit with him which proved very interesting. In the discussion period which followed the talk, Mr. Bellman answered questions for many members and guests who attended.

On February 17th, the New York Section will present Charles R. Wood, Jr., helicopter chief test pilot and manager of helicopter contracts at McDonnel Aircraft Corporation, in a talk entitled "The Development of the McDonnel Ramjet Helicopter." This discussion of McDonnell's "Little Henry Project" should prove interesting, particularly since Mr. Wood himself has a background that includes such things as an active part in "Operations Crossroads," the atom-bomb tests at Bikini Atoll.

Another ARS Section

THE American Rocket Society has established another Section—another indication of the growth of the Society among engineers and enthusiasts in the jet-propulsion field.

The first meeting of the New Mexico-West Texas Section of the American Rocket Society was held on Jan. 10, 1950, at Las Cruces, N. M. An exceedingly interesting talk on the "Possibilities of Interplanetary Voyages" was given by Wernher Von Braun to a group of approximately 285 people.

The Section will hold its first official election of officers on January 24, but until that time, the following men will act as temporary officers: J. P. Layton, chairman, Meetings Committee; J. R. Youngquist, treasurer; E. T. Munnel, chairman, Membership Committee; and J. B. Cray, secretary.

The enthusiasm of those attending the first meeting shows clearly that this Section will be a strong and active addition to the American Rocket Society.

ARS Pins

THE official emblem of the American Rocket Society is made up in pin form so that all members can wear it. Designed in silver and red, the pin has a clutch back and is one half inch in length; will not tarnish and is neat and striking. Have you ordered your ARS pin from the Secretary, ARS, 29 West 39th Street, New York 18, N. Y. Price is $2.

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